

Heavy Truck Engine Development & HECC

DE-FC05-00OR22805

Houshun Zhang, Ph.D.
Detroit Diesel Corporation

May 21, 2009

ace_42_zhang

Timeline

- Project start: February 2007
- Project end: March 2010
- Percent complete: 75%

Budget

- Total project funding
 - DOE: \$5 million
 - DDC: \$5 million
- Funding received in FY08
 - \$1.45 million
- Funding received in FY09
 - \$0.2 million

Barriers

- Limitations of fuel-injection technology;
- Lack of cost-effective controller management and calibration techniques;
- Inadequate integrated controls of engine and aftertreatment system;

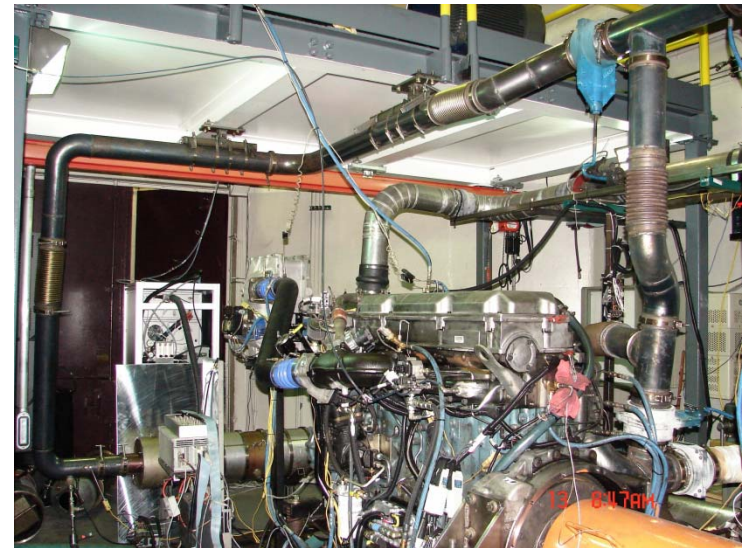
Partners

- Oak Ridge National Lab: Combustion
- Delphi: Fuel injection system supplier
- Atkinson: Control
- WERC: Combustion
- Quantlogic: Fuel injection nozzle
- Continental/Woodward: Combustion sensors



- Explore advancements in engine combustion systems using high-efficiency clean combustion (HECC) techniques to minimize cylinder-out emissions while optimizing engine fuel economy
- Emphasis on Enabling Sub-system Technologies
 - Advanced combustion system technologies
 - Flexible, precise fuel injection
 - Air and EGR system technologies
 - Advanced multiple input multiple output control technologies

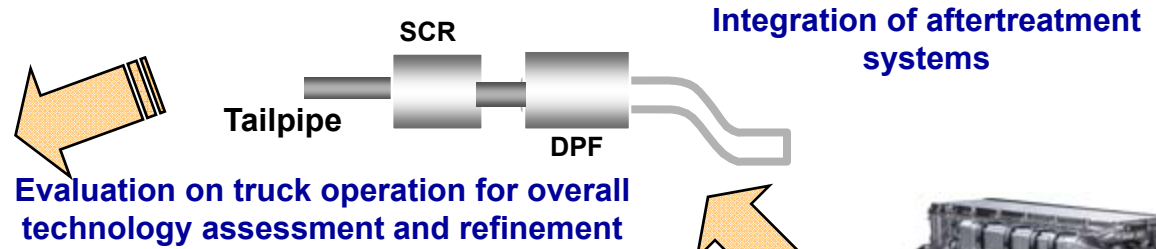
Multi-cylinder Test-bed



Month/Year	Milestone or Go/No-Go Decision
August - 2008	<p>Go/No Go Metric – Successfully complete development of the necessary individual subsystems to meet the performance targets.</p> <p>Milestone: 5% thermal efficiency Improvement with 2010 emissions</p> <p>Status: Completed and accepted by DOE in August 2008</p>
Sept - 2009	<p>Milestone - Complete engine systems integration with integrated controls and effective synergies with aftertreatment technologies</p> <p>Status: On schedule</p>

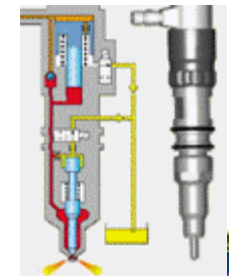
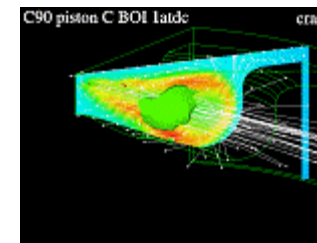
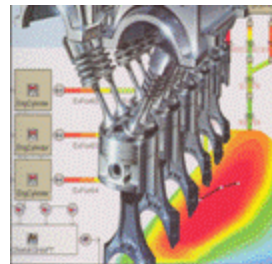
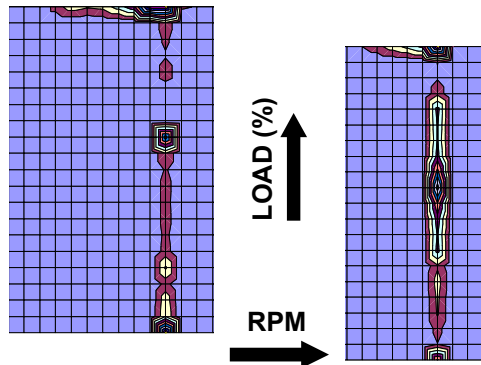


System Development Approach



Selecting road-load operating conditions

Steady State and Transient Dynamometer Testing



Example Operating Conditions Over Truck Routes

Integrated Analytical Simulation Tools

Component Optimization



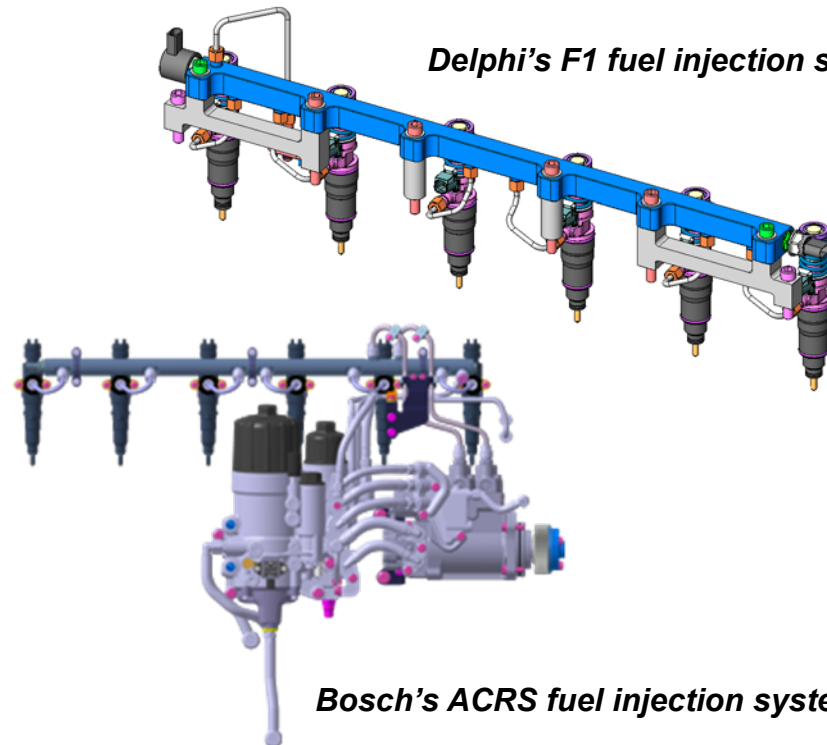
- Advanced fuel injection system with variable nozzle
- Innovative combustion system optimization
- Next generation control logic
- Real time combustion control



- Demonstrate potential of advanced injection system for achieving high efficiency clean combustion (HECC) mode operation for engine conditions consistent with HD drive cycles.
- Characterize emissions/efficiency for multiple high efficiency clean combustion strategies.



DDC engine at ORNL



Delphi's F1 fuel injection system

Bosch's ACRS fuel injection system



Micro-Variable Circular Orifice (MVCO)



First phase injection with conical spray and narrow spray angle



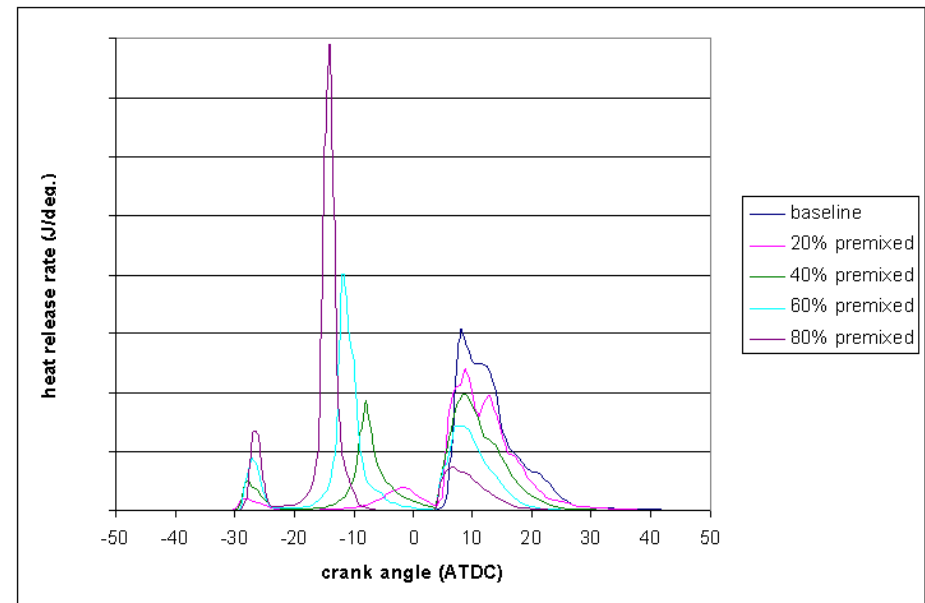
Second phase injection with multi-jet spray and wide spray angle

- Early analytical simulations demonstrated substantial thermal efficiency improvements with dual combustion mode realized by this variable nozzle technology
- More flow bench tests of Quantlogic nozzle are underway to simulate production engine operation
- Significant challenges exist in machining precision and needle control

Initial feasibility evaluated on successful fuel bench test of hardware



- Use of dual injectors is made to explore multi-mode combustion concept based on University of Wisconsin's extensive research and development
- Each injector is controlled by its own advanced flexible fuel injection system.
- Each injector system will be operated based on individual combustion mode requirements, such as spray angle, timing, phasing, fueling split in order to achieve optimal combustion efficiency
- The combustion analysis using KIVA on a production engine is being conducted
- Key technical challenge is whether two injector configuration can be fitted into the production engine cylinder head. Comprehensive CAD for feasibility study is being conducted.



Two injector design study initiated, to ensure continuation of two-stage combustion development independent of MVCO nozzle maturity



Combustion Optimization on PCCI

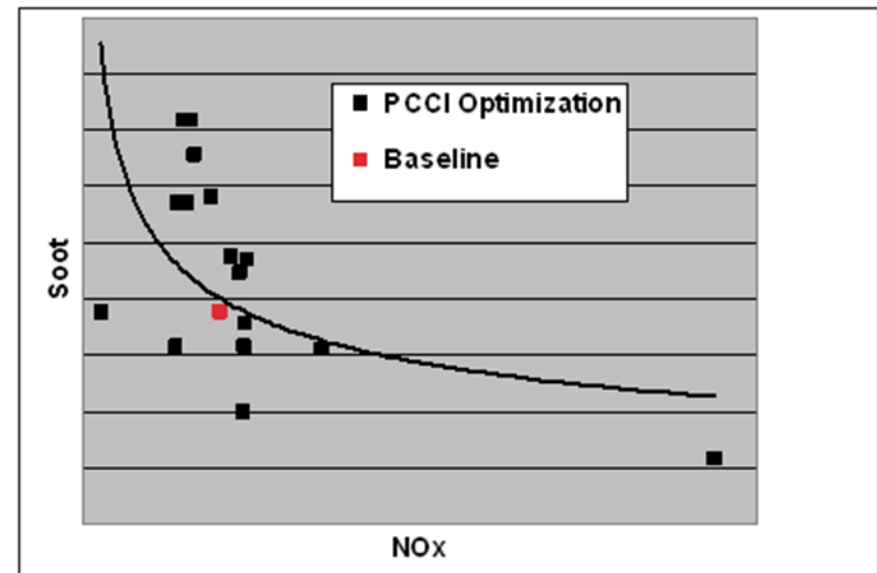
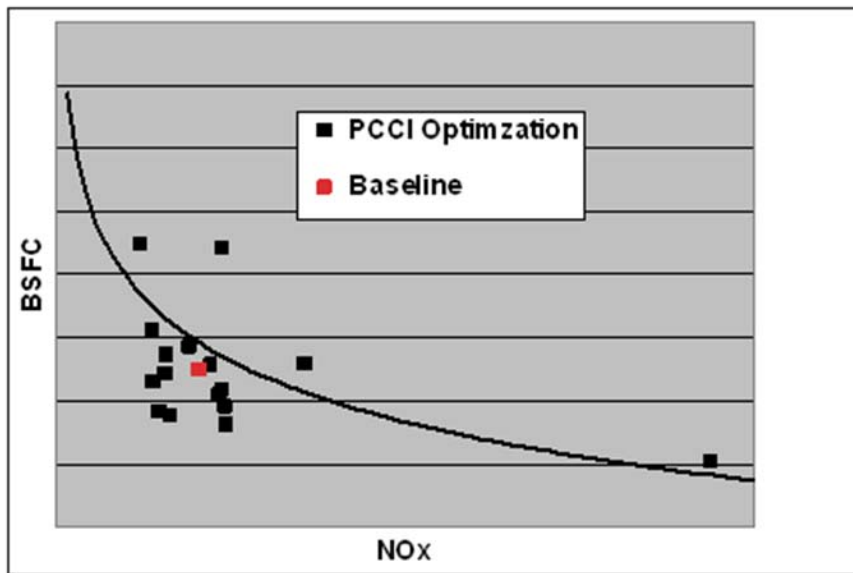
- Advanced combustion simulation tool (KIVA) is used for PCCI optimization, covering a wide range of injection timing, phasing, EGR rate, and boost.
- Analytically demonstrated potential for 10.8% fuel economy improvement at a single low load and low speed point while maintaining the same emission level as baseline.

run	Soot	NOx	gisfc	Fuel economy improvement
	g/kgf	g/kgf	g/kW-hr	%
base	0.23	3.24	233.3	-
1	0.12	5.27	201.1	13.8
2	0.41	7.76	223.0	4.4
-----	-----	-----	-----	-----
11	0.33	1.98	212.9	8.7
12	0.19	3.72	208.1	10.8

- These analytical results provide immediate guidance to explore engine tests experimentally for optimal thermal efficiency while maintaining the same emissions levels.
- It can significantly reduce development efforts with proper use of analysis

Combustion modeling leads the way to experimental evaluation

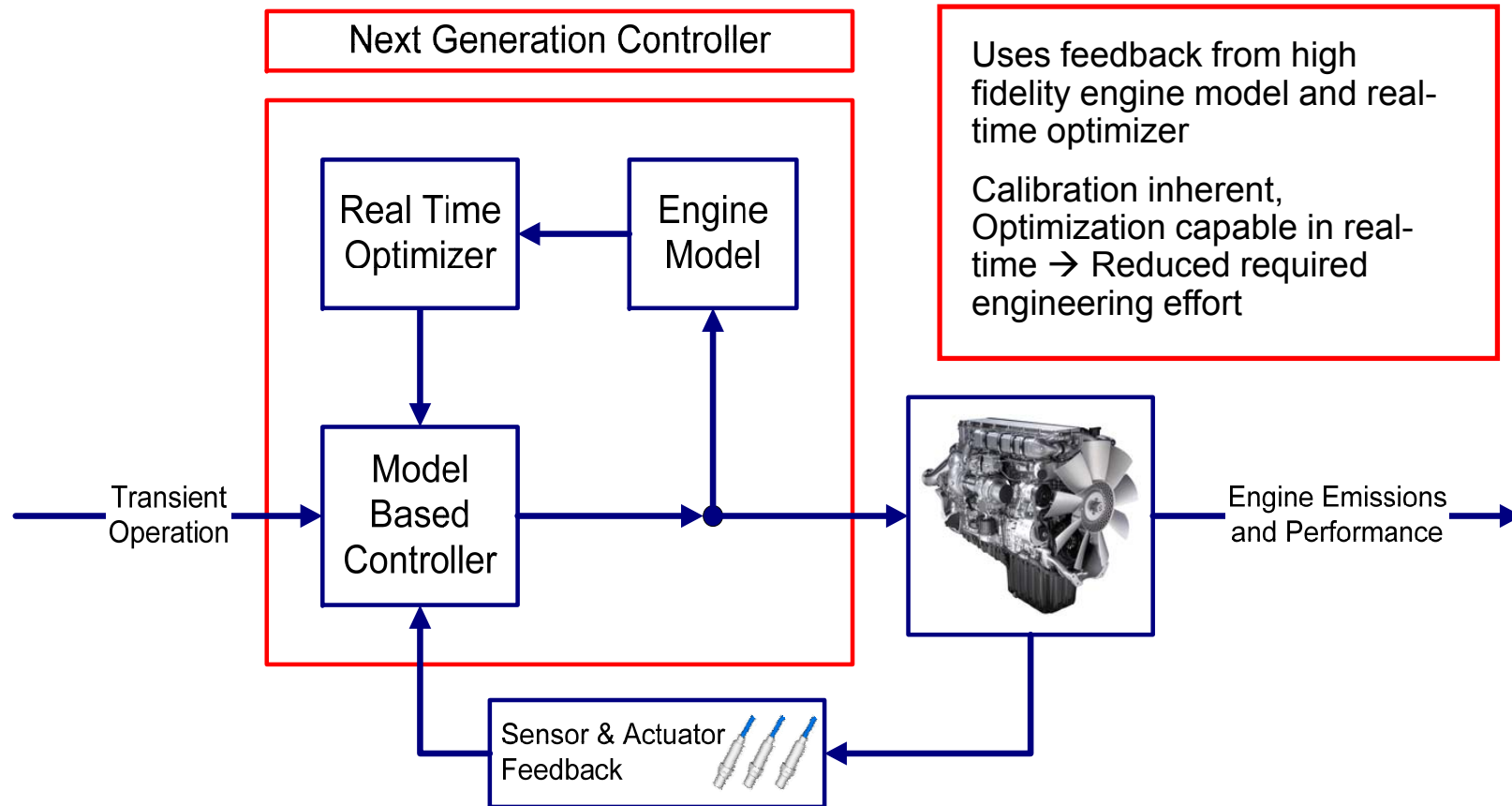




- Flexible fuel injection system allows to follow up analytical set points on injection timing, fueling, phasing, and multiple injection events, thus optimizing engine performance and emissions simultaneously toward the program goal
- Preliminary engine tests demonstrate 5% thermal efficiency benefits while maintaining about the same or lower emissions (NOx and PM)
- More engine testing is still underway in the hope to achieve the same thermal efficiency benefits as analytical work predicted

Analytically developed roadmap allowed to meet August 2008 Milestone

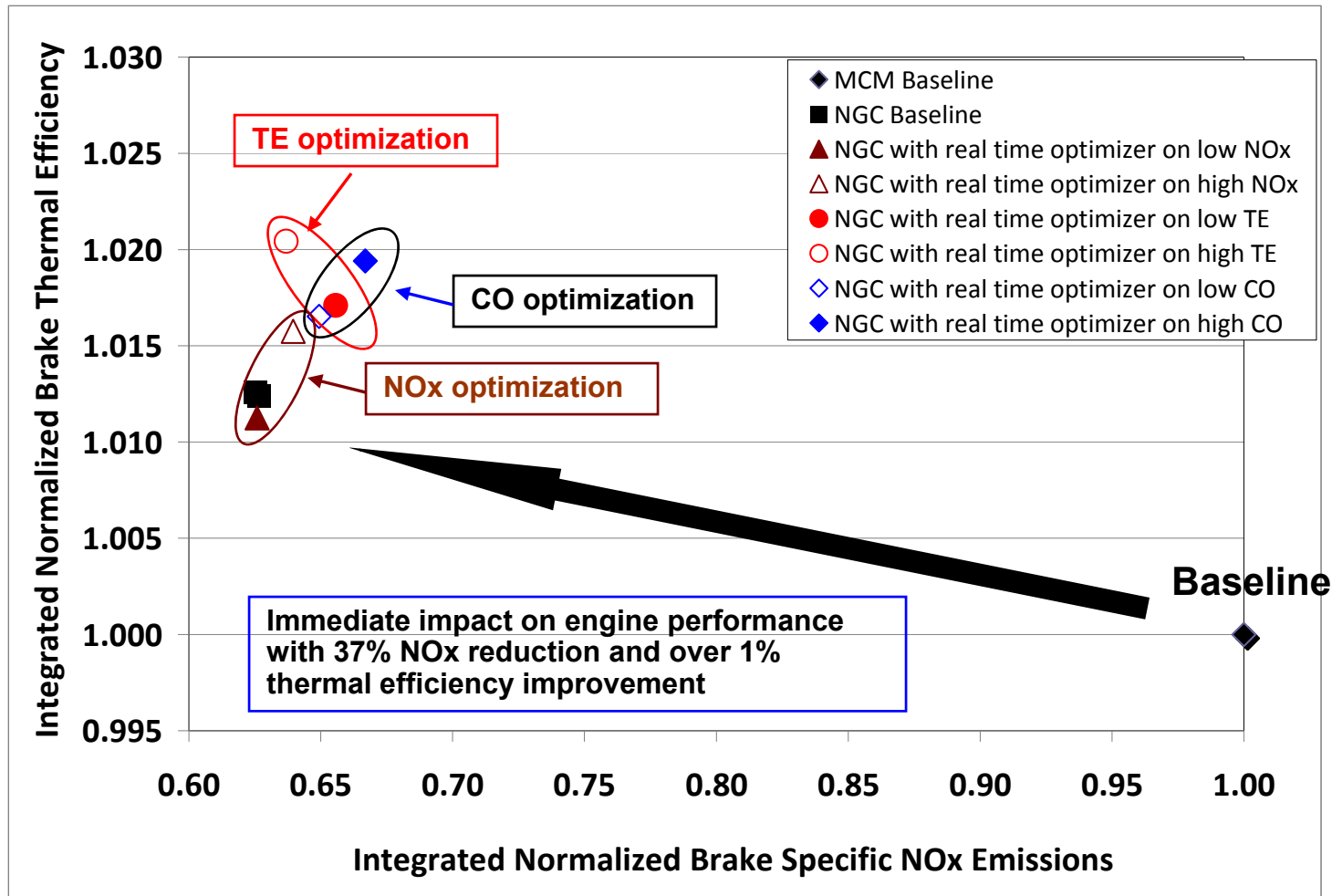




- Next Generation Controller (NGC) consists of sophisticated forward and inverse controllers plus real time optimizer and model based engine model
- Inverse controller produces 'optimized' control inputs for any engine speed and load demand, given the instantaneous engine operating parameter feedback, as well as the recent operating history of the engine and the trajectory of the control inputs.
- Engine model produces fully transient engine performance and emissions predictions in real-time that are then used by the Real-Time Optimizer to produce optimal time-based Control Inputs



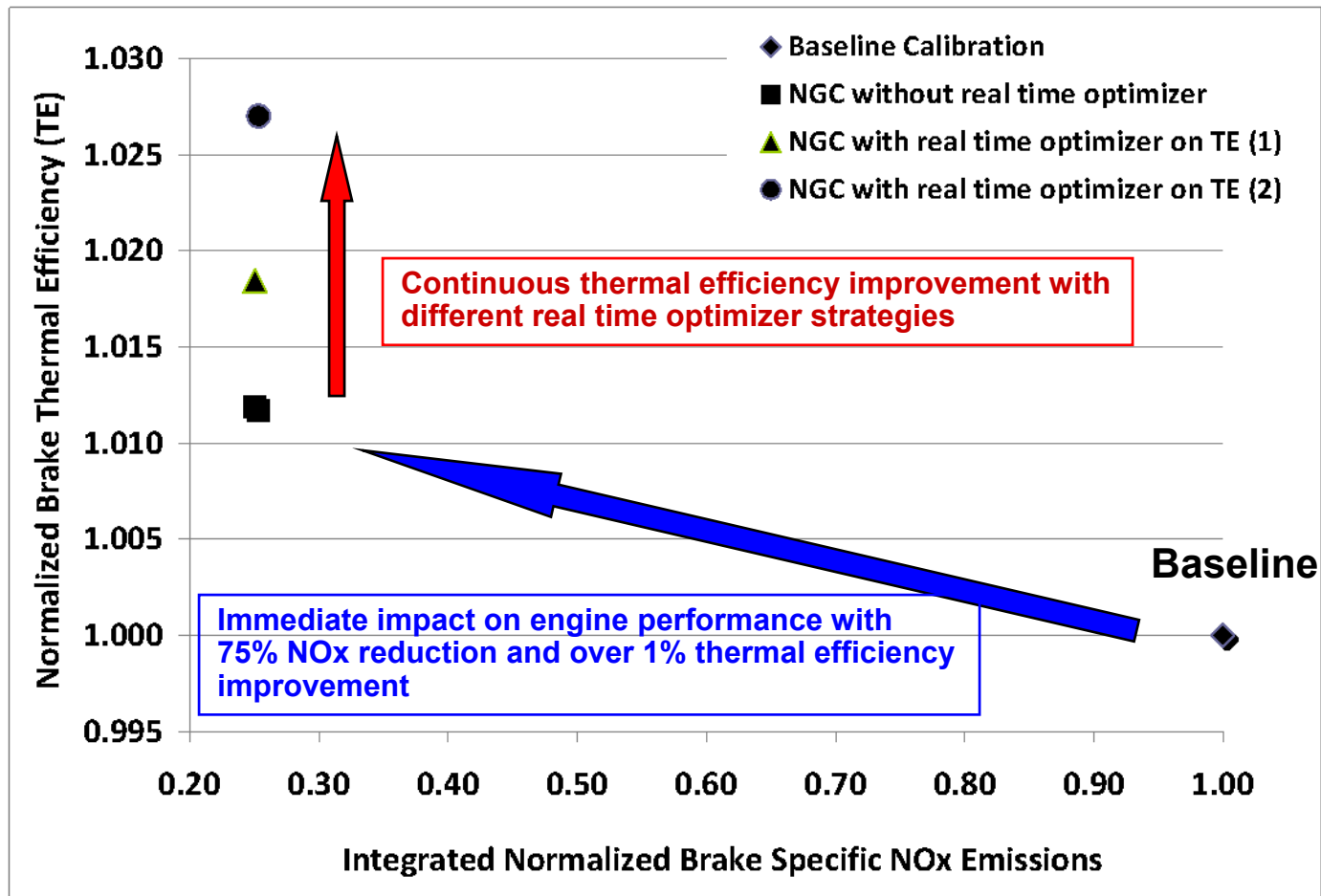
Next Generation Controller Optimization Transient Cycle 1



- Next Generation Controller (NGC) can easily set optimization objectives tailored to the application needs
- Advanced forward and inverse controllers plus real time optimizer and sophisticated model based engine model provide multi-task optimization with multi-objectives simultaneously



Next Generation Controller Optimization Transient Cycle 2

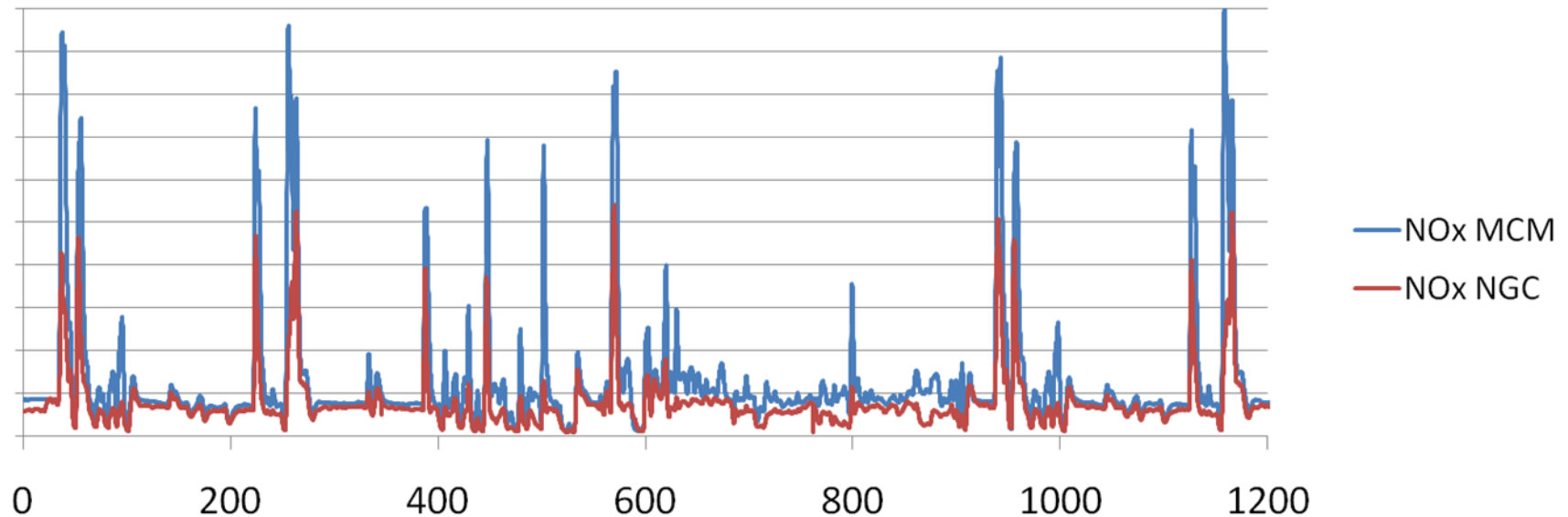


- Next Generation Controller (NGC) can specifically target thermal efficiency optimization toward program goal while simultaneously reducing emissions significantly
- 75% NOx reduction and 2.7% thermal efficiency improvement are obtained

NGC is still in the early development, but already shows promise



Comparison of FTP NOx Emissions for Baseline Control and NGC

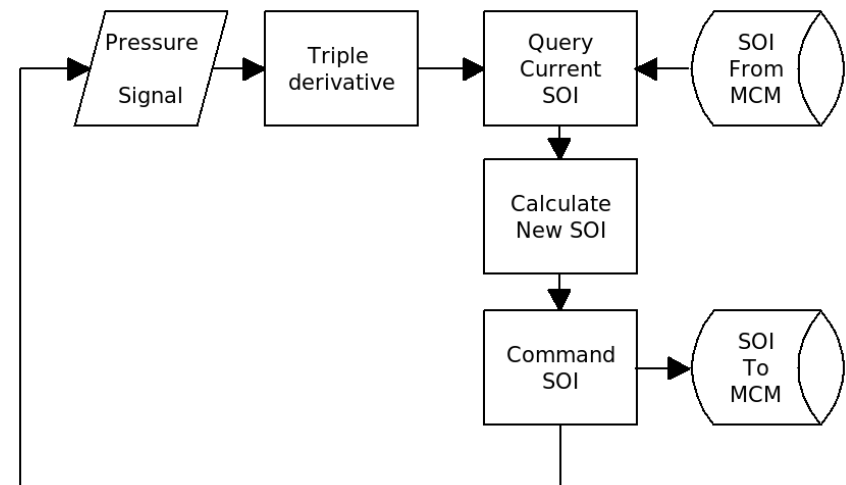


- NGC shows significant reductions in NOx over the FTP cycle.
- PM maintains similar level

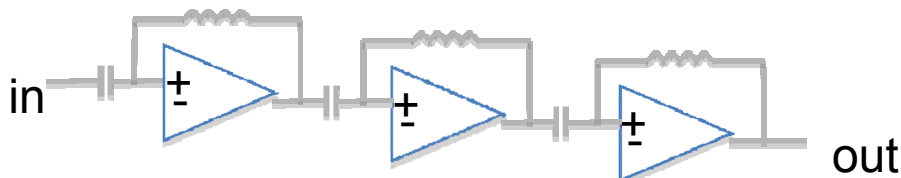
MCM – Motor Control Module



- Real time combustion control
 - Objective is to use closed loop control of combustion to achieve the necessary level of combustion timing control
 - Start of Ignition detection (SOI) is one of approaches
- Implementation of SOI determination
 - The third derivative can be calculated or determined by a simple circuit
 - To speed up the control loop, a hardware implementation was selected
 - Each functional group implements one differentiation on the input signal
 - The maximum value of the final output provides the SOI
- Validation and tests are underway



MCM: Motor Control Module



Integration of sensors on the engine cylinder head is completed



- Advanced next generation fuel injection system
 - Fully explore and validate all potential features of fuel injection system
- Variable injection nozzle technology
 - More flow bench validations are underway
 - Quantify the technical barriers before moving to the next step
- Multi-mode combustion mode exploration with enabled and advanced fuel injection for optimal thermal efficiency
- Next generation control development
 - Consolidate and validate the current developed control system for thermal efficiency optimization
 - Develop more robust and more reliable control system
- Transient combustion and control development
 - Real time combustion control using cylinder pressure sensors



Summary

- Program is progressing well toward meeting the program objective of thermal efficiency improvement.
- Experimentally demonstrated 5% thermal efficiency improvement with guidance of advanced combustion analysis
- Advanced analytical tools, if used properly, can play significantly role in shortening development cycle.
- Significant progress was made in next generation control development with substantial benefits in both thermal efficiency and emissions.



Acknowledgements

- Department of Energy Headquarters
 - Gurpreet Singh
 - Roland Gravel
- National Energy Technology Laboratory
 - Carl Maronde
 - Jeffrey Kooser

